ITT INDUSTRIAL LABORATORIES
A DIVISION OF INTERNATIONAL TELEPHONE AND TELEGRAPH CORPORATION
3700 East Pontiac Street
Fort Wayne, Indiana 46803
Area Code 219
Telephone 743-7571
TWX 241-2065

ITTIL 66-1018

March 30, 1966

SIXTH QUARTERLY REPORT

RESEARCH IN THE DEVELOPMENT EFFORT OF AN IMPROVED MULTIPLIER PHOTOTUBE

Contract No. NAS w 1038

National Aeronautics and Space Administration

Washington, D. C. 20546

Prepared by

F. H. Barr and E. H. Eberhardt

Approved by

S. M. Johnson, Jr., Manager
Advanced Product Development

M. F. Toohig, Manager
Tubes and Sensors Department

Dr. C. W. Steeg, Director
Product Development

TABLE OF CONTENTS

1.0 INTRODUCTION

This report is primarily concerned with the investigation of the dark current and dark counting characteristics of the FW-130 (S-20 cathode) series of ITTIL multiplier phototubes. The primary technique used in this investigation was that of cooling the tube, particularly the photocathode. Because of the necessity for obtaining a low over-all noise level and the ability to monitor cathode temperatures, some time was required to adapt the cooling equipment toward this end. Different modes of multiplier operation were also tried to determine their effect on multiplier noise.

In addition, this report includes data on some tubes built on other projects. The results of these tests bear directly on the purpose of this project and so were considered to be basically an extension of this NASA research effort.

2.0 EQUIPMENT DESCRIPTION

The multiplier phototube refrigerated chamber used in this work was a model TE-200 manufactured by Products for Research, Inc., of West Acton, Mass. This unit uses dry ice and alcohol as the coolant, and is capable of producing cathode temperatures of -68 degrees C in an ambient of 0 degrees C to +40 degrees C. It has a removable double plexiglass input window at one end and the other end of the chamber is fitted with an "O" ring sealed socket assembly in which the voltage divider may be potted. High voltage input and collector output connector are included on this assembly. Because of the versatility required of this equipment, the socket assembly was modified so that the dynode leads came out through a shielded cable and were terminated in a 20 pin tube base so it could be plugged into the standard test fixture. In addition to this, two teflon insulated wires and a chromel-alumel thermocouple were brought out through this assembly from the cold chamber so that control potentials could be applied to such special electrodes as the cascade aperture. This also allowed the cathode temperature to be monitored. All leads through the socket assembly were potted in place to prevent air leakage and subsequent frosting.

While this cooler in general is quite satisfactory, there are two points where careful grounding are necessary to assure low noise performance. First, there must be a ground strap between the collector coaxial output connector, which is mounted in the side of the bakelite socket assembly, and the aluminum cover through which the shielded cable is brought out. This strap is necessary even though these two parts are grounded by way of the cable shields.

Secondly, it was discovered that the coolant tank around the multiplier tube is electrically floating as the cooler is supplied. After consulting the manufacturer, it was found possible to remove the front cover of the cooler, remove a small amount of the foam insulation surrounding the filling port and fasten a ground strap to it. This strap was brought out through a hole in the top of the case where it was fastened to a lug under one of the front plate mounting screws. The foam insulation removed during this procedure was then replaced.

A further source of difficulty was found with the pulse preamplifier-multichannel analyzer combination. While these two instruments (Tennelec Model TC-M-170 preamplifier and TMC Model 101-100 channel analyzer) functioned properly in themselves, they were not compatible as they were received from the manufacturer due to pulse shape considerations. This incompatibility takes the form of non-linearity in the last half of the memory, channels 50 to 100. On checking with the Tennelec Instrument Company, it was discovered that the preamplifier should have been modified, before delivery, so that the preamplifier output pulse shape matches the input requirements of the TMC-101 Analyzer. At the present time, the nuclear instrumentation industry is not standardized on the input pulse characteristics of multi-channel analyzers, but only on the input of the more expensive, high quality, linear amplifiers. This occurs because most users bypass the linear amplifiers in the analyzer and couple directly from an external linear amplifier into the analyzer ADC circuit. For this reason, prospective users of equipment similar to that used in this laboratory would be well advised to carefully check these considerations with the instrument supplier if they intend to purchase such equipment.

Our preamplifier has now been modified and the remaining non-linearity in the system is less than 2 percent. An additional improvement in the operation of the preamplifier (as a result of this modification) is the increased signal-to-noise ratio. Measured noise at the output of the preamplifier before modification was 5 mv; after modification, it was 2 to 2.5 mv. (This improvement was predicted by the manufacturer.)

As a result of these modifications, the over-all noise reduction has enabled us to count pulses of about half the amplitude as before without counting noise pulses which originate outside the tube.

3.0 COOLING TESTS

One of the primary uses of multiplier phototubes is in astronomical applications where high quantum efficiency and low noise are required for maximum information acquisition. Because it is usually desired to push the multiplier phototube to its fundamental limit of sensitivity, namely, counting charge pulses at its output, dark noise pulses must be reduced to a level where signal pulses can be counted with minimum ambiguity. Assuming that dark pulses are primarily due to thermionic emission in a well designed tube, it should then be possible to cool the photocathode to substantially reduce these pulses. For S-1 photocathodes, the thermionic emission characteristics are well known, and Richardson plots of the dark current versus temperature have been reported.[1] In the case, however, of the S-20 trialkali cathode, this information is not readily available. Since this type of cathode has a high visible sensitivity from 3500 Å to 8500 Å, it is useful to stellar spectrometry, and in certain laser applications where the available radiation may be quite small. For this reason, it was considered essential to investigate the cooled mode of operation of tubes with this cathode to determine what could be expected in terms of improved signal-to-noise ratio.

The cooling experiments were carried out in the following manner. With a tube enclosed in the cooler and all connections properly made, a dark current reading and a dark count were taken at room temperature. The temperature of the cathode was then reduced by filling the coolant tank. Actually, a somewhat more convenient method used was to blow dry nitrogen gas, cooled by liquid nitrogen, into the coolant tank. When a temperature of -60 degrees C was reached, the flow of the cold gas was reduced and the system allowed to come to equilibrium. The tube temperature was then raised by blowing warm air from a heat gun into the coolant chamber, and data was taken at 10 degree intervals, as the tube warmed up. Figures 1 and 2 are a series of curves showing the d-c dark current as a function of temperature for five tubes with S-20 cathodes. These tubes are standard pilot production tubes. The most obvious feature of these curves is the limited reduction in dark current due to cathode cooling. For S-1 cathodes it is not unreasonable to expect three to five orders of magnitude reduction in dark current for 50 degrees C reduction in temperature. This data, however, fails to show similar results for S-20 cathodes. One exception was found in the case of F64-974-30 which is a special tube designed for wide dynamic range counting applications. The tube is constructed with the glass image section envelope connected to the metal multiplier section envelope by a heliarc weld ring. Aside from its unusual glass-metal envelope, it has an additional innovation in the collector stem lead. This lead is coaxial in design and comes out at the center of the stem. The anode itself is mounted on the center conductor in such a way as to be isolated from the photoceramic multiplier support members. This type of construction thereby eliminates possible leakage across the multiplier supports and may provide better isolation of the anode lead through the stem as well as more effective shielding from stray pickup noise. It would seem, then, from this assumption that in the case of the other tubes, the dark current curves bottom out on some d-c leakage level set by the condition of the glass stem and the ceramic multiplier support members. However, some of the standard tubes come within half an order of magnitude of the characteristics of this special tube.

A summary of the pertinent data is included with some calculated parameters in the table of Figure 3. The first seven columns are self-explanatory. Column eight is the measured d-c anode dark current for the two extreme temperatures (+20 degrees C and -60 degrees C) for the curves in Figures 1 and 2. In column nine is recorded the corresponding photocathode dark count density which was taken at the same time the dark current was read. In column ten is the equivalent dark current density based on

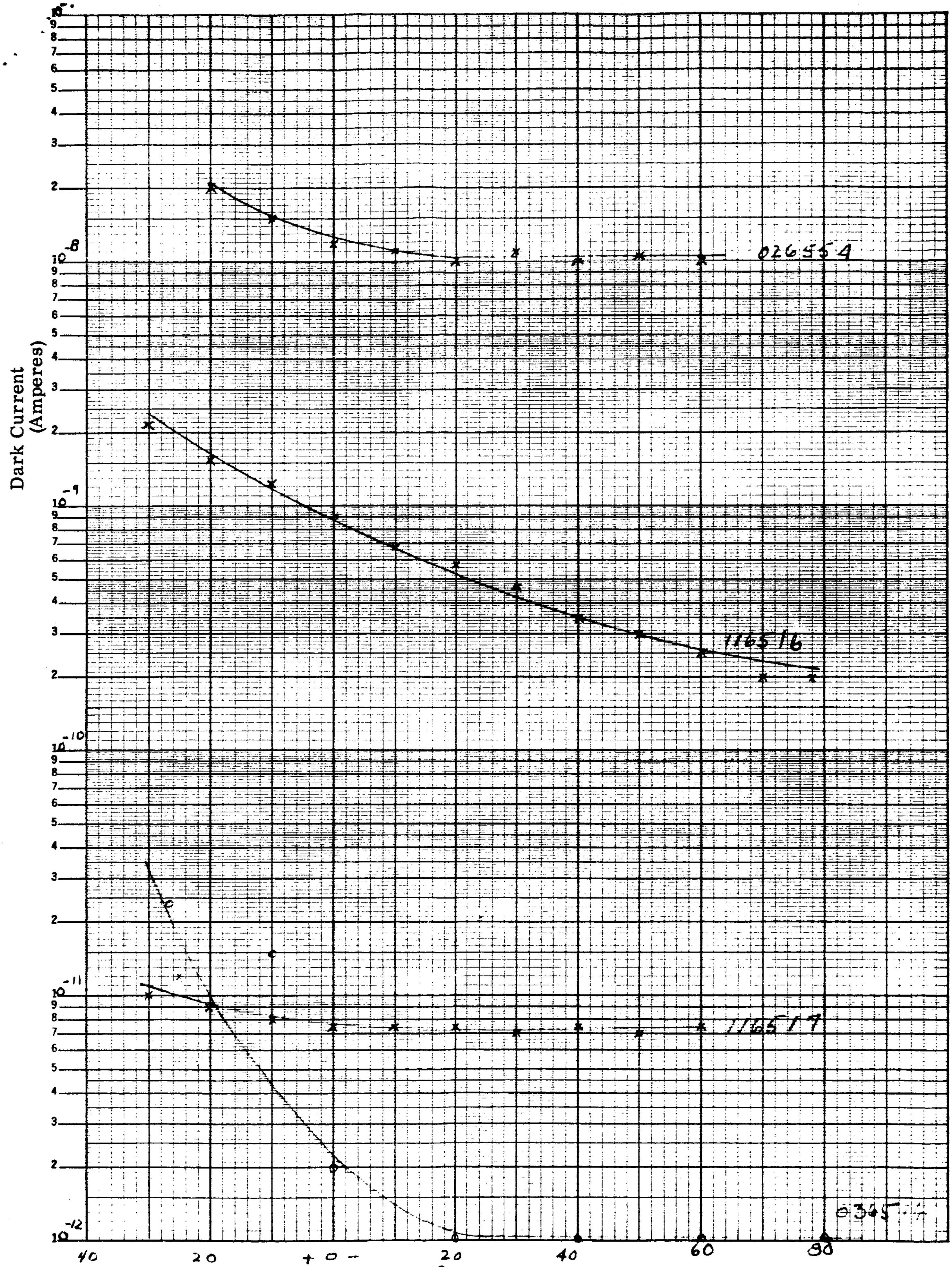

Dark Current (Amperes)
Temperature (°C)
026554
116516
116517
0345

Figure 1

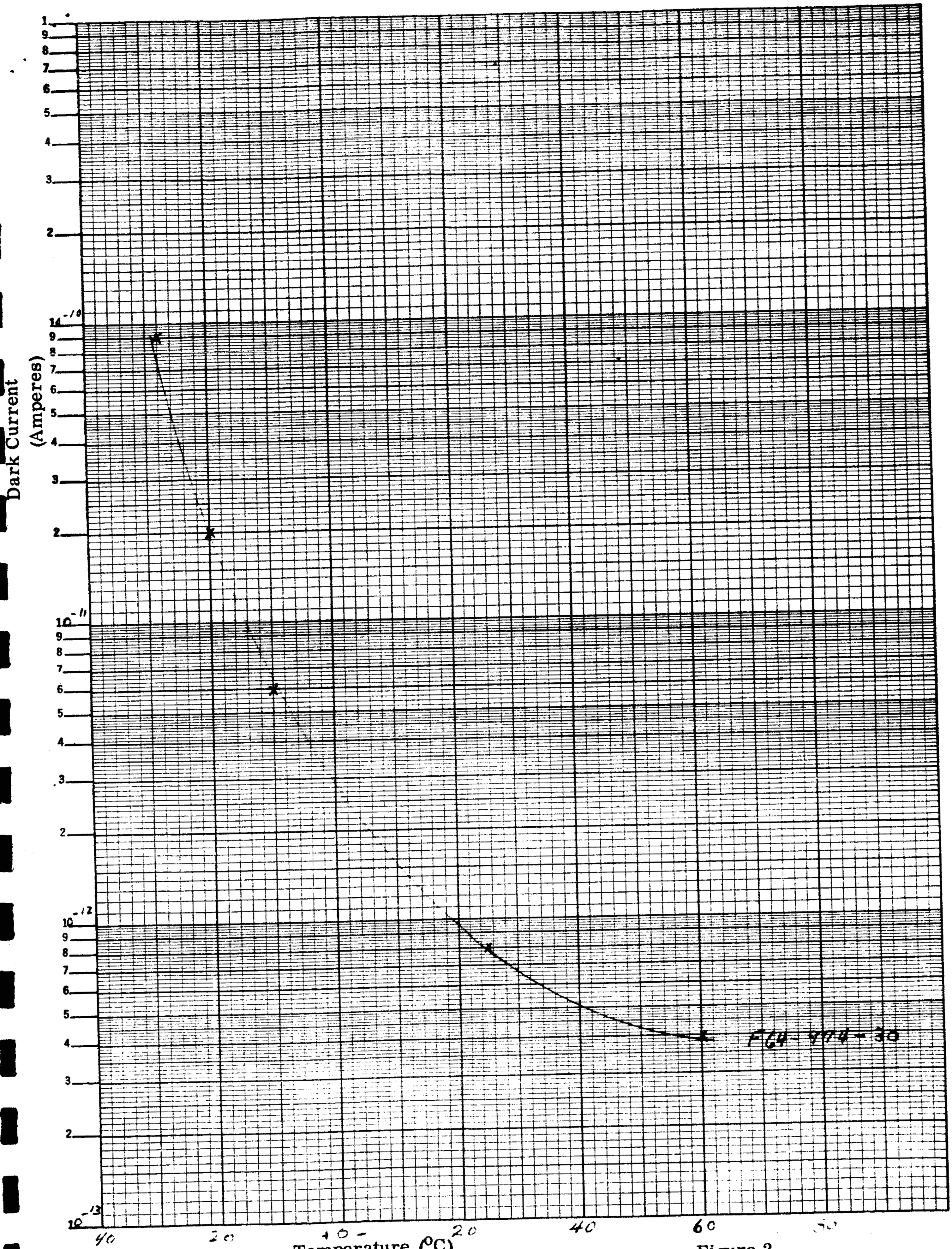


Figure 2

1	2	3	4	5	6	7	8	9	10	11
Tube Number	Operating Voltage	Average d-c Gain	Cathode Sens. ($\mu a/l$)		Cathode Area (Cm^2)	Cathode Temp. (^oC)	Measured d-c Anode Dark Current (Amperes)	Photocathode Dark Counts Per Cm^2 Per Second	Equivalent Photocathode Dark Current Density ($Amps/Cm^2$)	Photocathode Dark Current Density ($Amps/Cm^2$)
			2870^oK Tungsten	Corning 2030 Filter						
116517	1800	1.2×10^6	105	12	.62	20	1.0×10^{-11}	561	8.9×10^{-17}	1.3×10^{-17}
						-60	7.5×10^{-12}	10	1.6×10^{-18}	1×10^{-17}
116516	1800	2×10^6	105	10	.62	20	2.2×10^{-9}	8920	1.4×10^{-15}	1.8×10^{-15}
						-78	2.0×10^{-10}	827	1.3×10^{-16}	1.6×10^{-16}
026554	1800	3.6×10^6	100	20	.62	20	3.0×10^{-8}	1080	1.7×10^{-16}	1.3×10^{-14}
						-60	1.0×10^{-8}	387	6.2×10^{-17}	4.5×10^{-15}
036516	1800	8×10^5	98	16	1.27	20	6.5×10^{-12}	157	2.5×10^{-17}	6.4×10^{-18}
						-60	1.0×10^{-12}	9	1.4×10^{-18}	1×10^{-18}
F64-974-30 12 Stage Multi-plier	2000	1.6×10^5	160	60	1.27	28	9.0×10^{-11}	2310	3.7×10^{-16}	4.4×10^{-16}
						-60	4.0×10^{-13}	Dark Count Obscured By Noise Pickup		2×10^{-18}

Figure 3

this dark count density for comparison with the dark current density based on d-c measurements. Column eleven is the dark current referenced to the cathode using the average d-c gain figures in column three and the cathode area in column six.

A comparison of the data in column eight and ten shows immediately the wide differences in the measured dark current density and the equivalent dark current density which implies that the dark current, on cooling, flattens off at the d-c leakage level. The same characteristic seems to be present in the dark count data for there is approximately the same reduction in dark count with cooling as in the case of dark current.

In checking the assumption made earlier, that the d-c anode dark current may be bottoming out at the d-c leakage level, it is of interest to compare the data in columns ten and eleven. In the case of tubes 116517, 116516, 036516, and F64-974-30 there is good agreement, within approximately an order of magnitude, between the equivalent dark current density and the cathode dark current density.

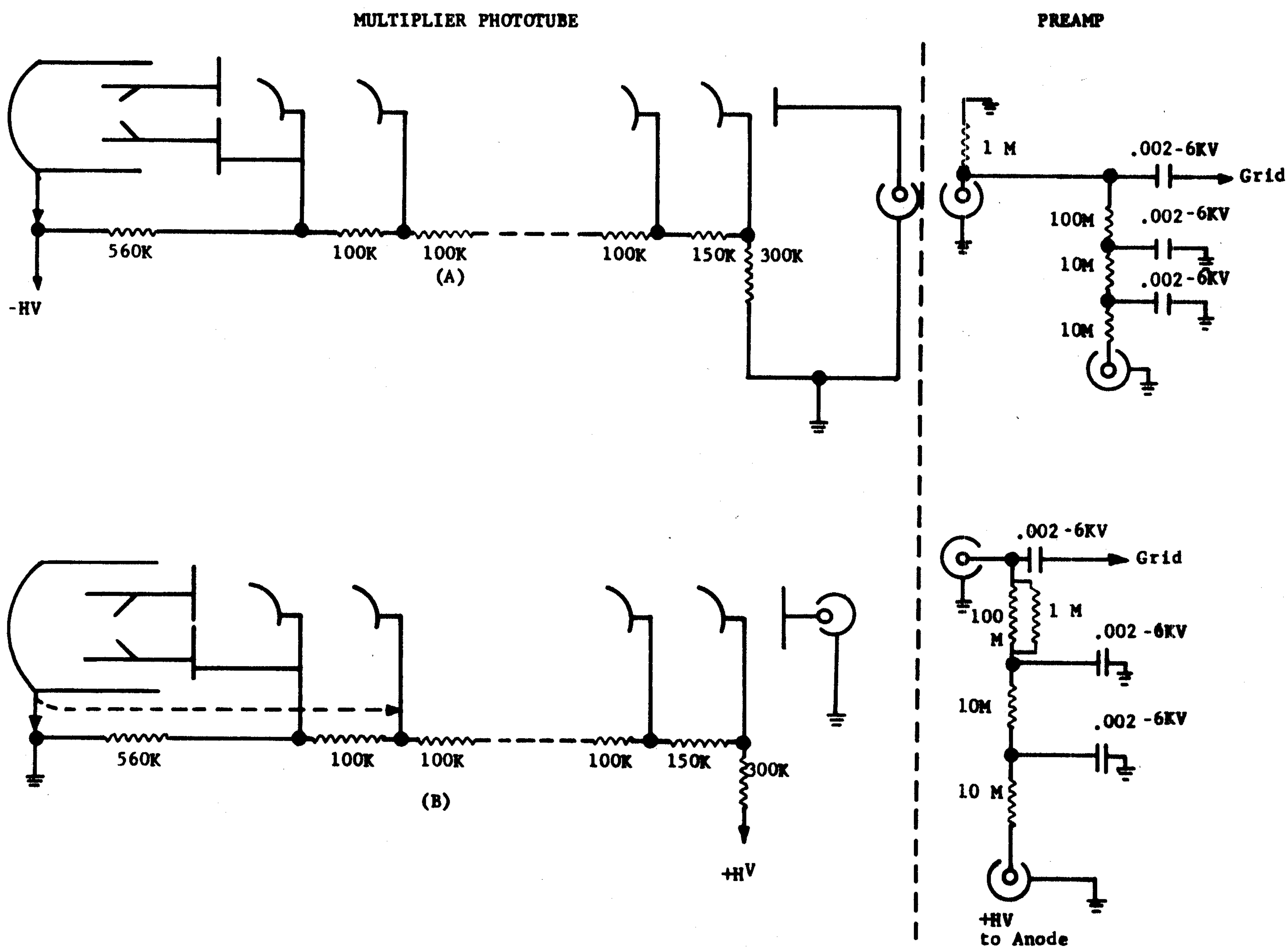
The differences in the data may be, at least in part, explained by the statistical nature of multiplication process for single events as compared to the average d-c methods of measuring gain. The agreement noted above, indeed, indicates that the dark current of these tubes on cooling does approach a limit that is essentially that of the cathode dark count density level and further that the room temperature thermionic emission level is only slightly higher. F64-974-30 is the exception to this for it has a sensitivity, in the spectral region beyond 7000 Å, of 3 to 6 times that of the other tubes. This is not an unexpected result for one would expect such increased thermionic emission with increased red sensitivity, the S-1 cathode being a case in point. Tube number 026554 does not show the agreement between equivalent dark current density and cathode dark current density that the other tubes do. Both at room temperature and at -60 degrees C, the cathode dark current density is two orders of magnitude higher. Since the cathode dark current density is the d-c anode dark current referenced back to cathode. This difference is apparently d-c leakage in the anode circuit. This leakage, undesirable as it may be, does not seeem to contribute to the dark count. As a result of this condition two orders of magnitude improvement in sensitivity was obtained by applying counting techniques, or opposed to d-c measurement, to the output circuit for this particular tube.

In trying to explain the behavior of tubes, e. g. number 026554, where cooling did not produce the expected dark current reduction, a problem that was given consideration was that of light generation by the phototube itself due to corona in the image section. For this purpose, a second multiplier with a very low dark counting rate was enclosed in a light-tight fixture and coupled to the window mounting ring of the cooling chamber. A dark spectrum was run for this tube with no voltage applied to the tube under test and following that a second count was taken, but with high voltage applied to the tube in the cooling chamber. No additional counts were recorded from the tube "looking" at the test tube even with an additional 400 or 500 volts applied to the tube being tested. Similar tests were made in a different enclosure so that the tube under test could be inspected in other areas, such as the aperture-dynode 1 region and the collector region. In no case was it possible to detect any kind of arcing or fluorescense which might be responsible for regenerative feedback to the photocathode. While such effects have been reported[2], they were detected in tubes during high peak anode currents, and the glow produced was in the collector region of the tube.

Another problem area investigated was the effect of multiplier phototube ground point on the noise content. For many applications, the tube is operated with the cathode at high negative voltage and the anode at ground as shown in Figure 4 (a). For operation of the multiplier with the cathode at ground potential the modified divider is shown in Figure 4 (b). Since the high voltage signal coupling capacitor and decoupling network are supplied in the preamplifier itself, the only actual changes that had to be made were: (1) at the tube socket and (2) to shunt the 100-megohm resistor in the decoupling network with a 1 megohm resistor to maintain very nearly the same load impedance. The tube operation was quite satisfactory in this mode of operation, but it was discovered that when the cathode was connected to dynode 2, (i.e., biased off), as shown by the dashed arrow in Figure 4 (b), there still remained some large pulses, 3 to 5 times the amplitude of a single electron pulse, with a rate of about 300 or 400 per minute. This was quite different from the previous mode of operation, for in that case no pulses appeared in the output of the tube. Since the high voltage for the anode was applied through the preamplifier high voltage type BNC connector, it was suspected that signal input BNC connector of the low voltage type might be arcing to ground. When the preamplifier, however, was disconnected from the tube test fixture, the pulses stopped. On reconnecting the preamplifier to the test fixture and applying high voltage (but leaving the tube out of the socket), the pulses appeared again at the same rate. This indicated that the difficulty was arcing in the socket which was a Cinch Jones Type 20-PM cast of MAL-60 alkyd glass fiber material.

There did not seem to be any appreciable difference in these two modes of operation except for the noise introduced by arcing in the socket. The decision, therefore, as to grounding the cathode or anode of a multiplier phototube should be made on the basis of amplifier input coupling and insulation or other special conditions. If for any of these reasons, however, operation with anode at high positive potential is desirable, the user would be well advised to use another socket, if available, or to machine an appropriate socket out of teflon.

Figure 5 demonstrates one other aspect of the dark noise which has often been mentioned by multiplier phototube users, mainly the decay of the dark current or dark count with time. Out of the tubes tested, two showed a measurable effect.



MULTIPLIER PHOTOTUBE
PREAMP
560K
100K
100K
(A)
100K
150K
300K
-HV
1 M
.002-6KV
Grid
100M
.002-6KV
10M
.002-6KV
10M
560K
100K
100K
(B)
100K
150K
300K
+HV
.002-6KV
Grid
100 M
1 M
.002-6KV
10M
.002-6KV
10 M
+HV
to Anode

Figure 4.

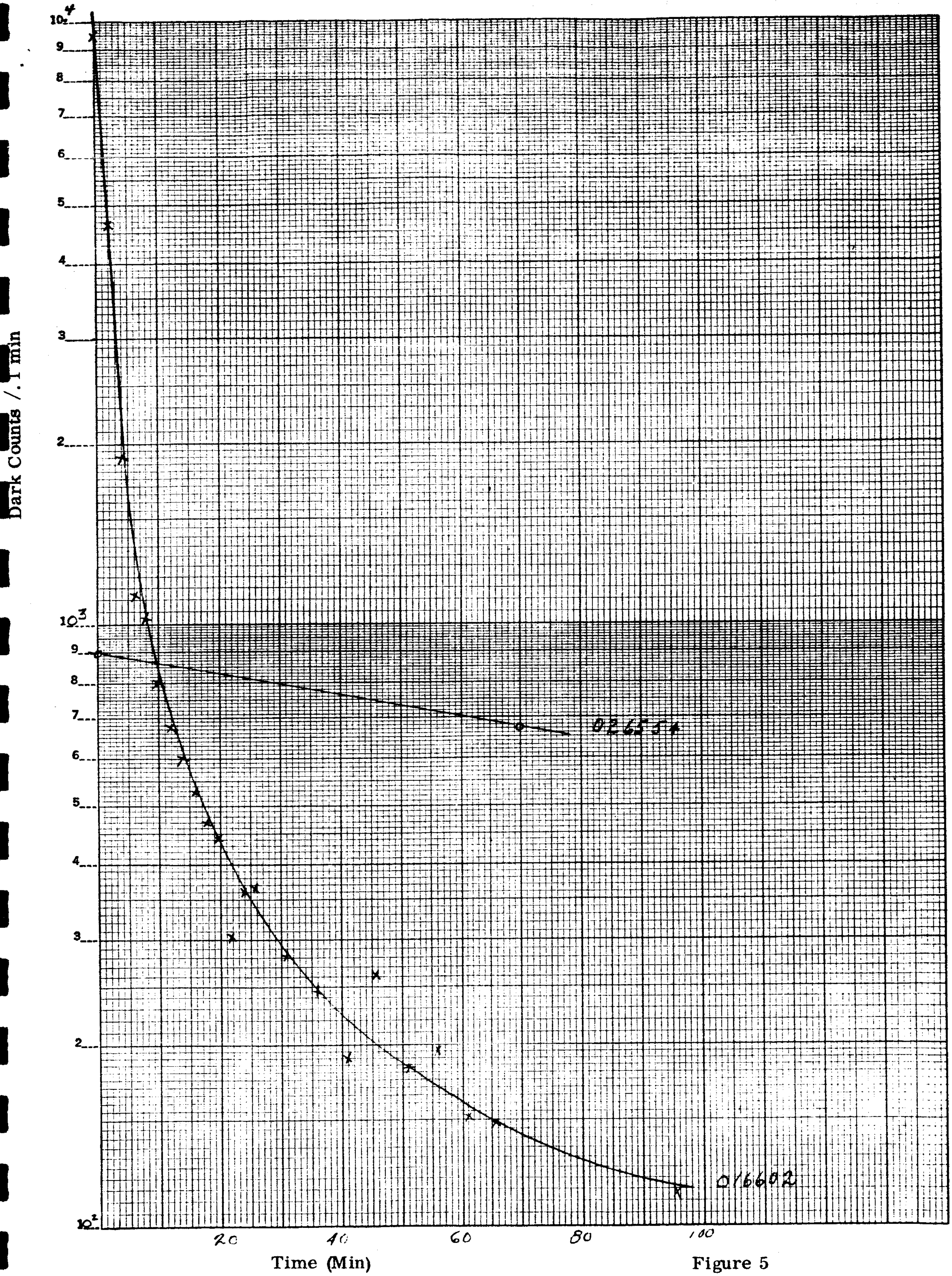

Dark Counts /.1 min
10^4
9
8
7
6
5
4
3
2
10^3
9
8
7
6
5
4
3
2
10^2
20
40
60
80
100
Time (Min)
026554
016602

Figure 5

The measurements were started immediately after the tube was placed in the dark enclosure and high voltage had not been applied to the tube while exposed to room level illumination. The data could be repeated simply by turning off the high voltage, lifting the dark enclosure cover, replacing the cover and again applying high voltage to the tube.

This would indicate that in low level counting applications, at least some tubes will require care in handling so that this situation does not render the data useless during the early minutes of operation.

4.0 LARGE AND VARIABLE AREA CATHODES

As mentioned in the last quarterly report, some work is being done in this laboratory on another contract[3], on multiplier phototubes with larger cathodes (0.5 inch in diameter).

Recently, several tubes have been built with the cascade aperture design in an effort to improve their single electron response. The data in Figure 6 was taken on tube number F65-974-30, whose cooling characteristics were reported in the previous section of this report, with the cascade aperture at limiting aperture potential. The top curve is the total spectrum which included signal, thermionic, and dark emission. Note the absence of the rising characteristic in the early channels. This spectrum has a peak-to-valley ratio of 1.13.

The second curve is with the cathode illumination turned off so that only the thermionic and dark emission remain. Here a larger number of small pulses appear and there is no valley, but the general shape of the signal spectrum is maintained, undoubtedly because of the cathodes higher red sensitivity (16×10^{-3} A/W @7000 Å).

The dark spectrum is shown in the lower curve at a temperature of -60 degrees C. In the region of the peak of the signal spectrum, there are an average of only four counts per channel per tenth minute.

Figure 7 is data taken from the same tube, but with the cascade aperture at -45 volts with respect to the limiting aperture. The total spectrum has a somewhat better peak-to-valley ratio, 1.26, while the thermionic spectrum also has a peak, with a peak-to-valley ratio of 1.09. Inspection of the dark spectrum shows a significant change. Channels two and three have a reduction of more than 50 percent in the total counts per channel and there is an average of less than three counts per channel per tenth minute in the region of the peak.

A more recent innovation in the design of the aperture-to-dynode 1 area was made in a multiplier phototube (a FW-129 type), on yet another contract[4]. In this tube,

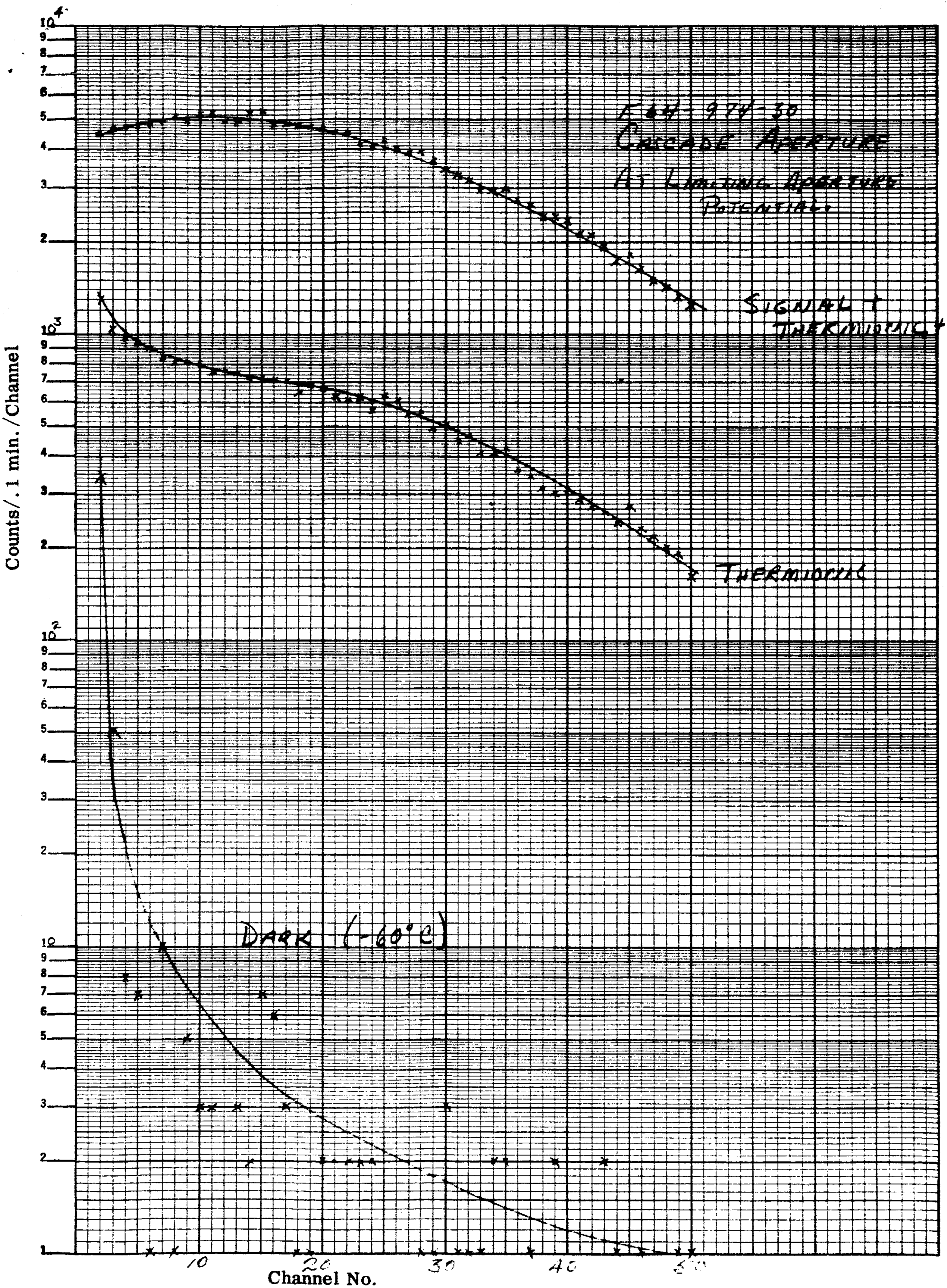

Counts/.1 min./Channel
Channel No.
CASCADE APERTURE
SIGNAL +
THERMIONIC
DARK (-60°C)
10
20
30
40

Figure 6

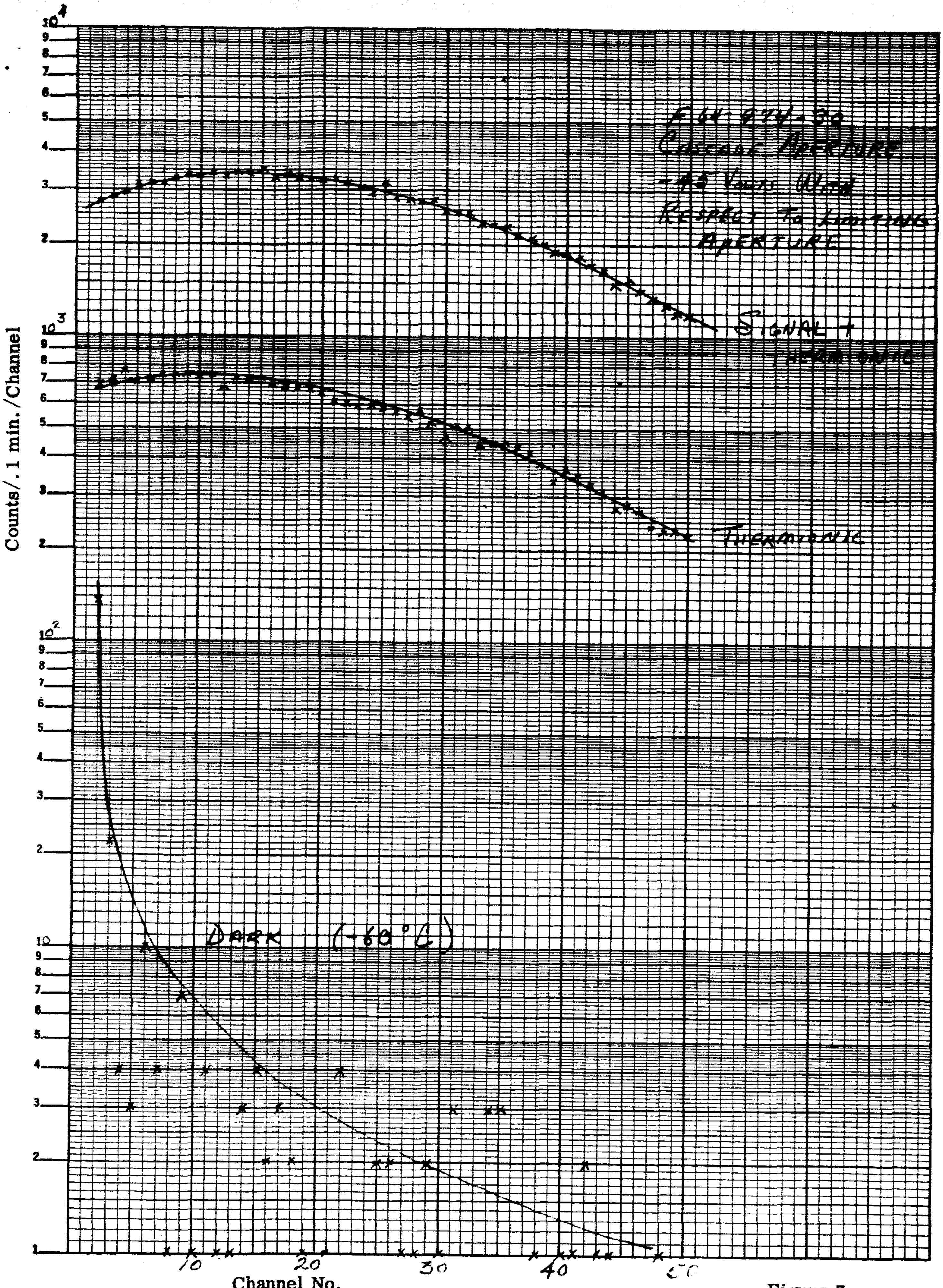

Counts/.1 min./Channel
Channel No.
Signal + Thermionic
Thermionic
Dark (-60 °C)
Cascade Aperture
With Respect to Limiting Aperture

Figure 7

the limiting aperture and cascade aperture are operated at the same potential and a third and smaller aperture is placed between them to form an einzel lens configuration. The net result of this design is to produce a variable electronic aperture when the center aperture is operated at a negative potential with respect to the photocathode. The ability to adjust the diameter of this aperture thus provides a means of selecting the instantaneous effective cathode diameter (IEPD). As pointed out in an earlier report, restricting the cathode area is a major contributing factor to good counting characteristics.

Figure 8 shows the effect of varying the center aperture from cathode potential (0 volts) to -9 volts. As the potential is made more negative, the IEPD is decreased and a corresponding decrease is seen in the total count. The location of the single electron peak, however, remains unchanged, indicating that the gain of dynode 1 is not affected. A further interesting characteristic is the nearly constant peak-to-valley ratio. This ratio varies from 1.45 to 1.58 with an average value of 1.51. Of equal importance is the very low dark counting rate. In no case is the total count per channel in the region of the peak more than two, and in other channels one or zero.

It is not yet known if this low dark counting rate is truly a property of this aperture-dynode 1 configuration since only one such tube has been constructed, but it is of sufficient interest to merit further investigation.

5.0 CONCLUSIONS

From the foregoing data it seems apparent that, for the tubes tested, reasonable correlation is obtained between the photocathode dark current density and the photocathode dark count density. Furthermore the cathode dark current is not as temperature sensitive as one would expect based on the normal behavior of thermionic emission. The mechanism responsible for this behavior is not known, therefore further investigation of basic S-20 cathode characteristics as well as the over-all tube operation is needed.

REFERENCES

1. ITTIL Application Note E4

2. G. Pietri, IEEE Trans on Nuclear Science, Vol. NS11, 1964, page 76.

3. University of California, Lick Observatory NASA Prime Contract 05-003-100-1 (Subcontract to ITTIL, G607170)

4. Line Scan Dissector, USAF Contract No. AF53(615)2626

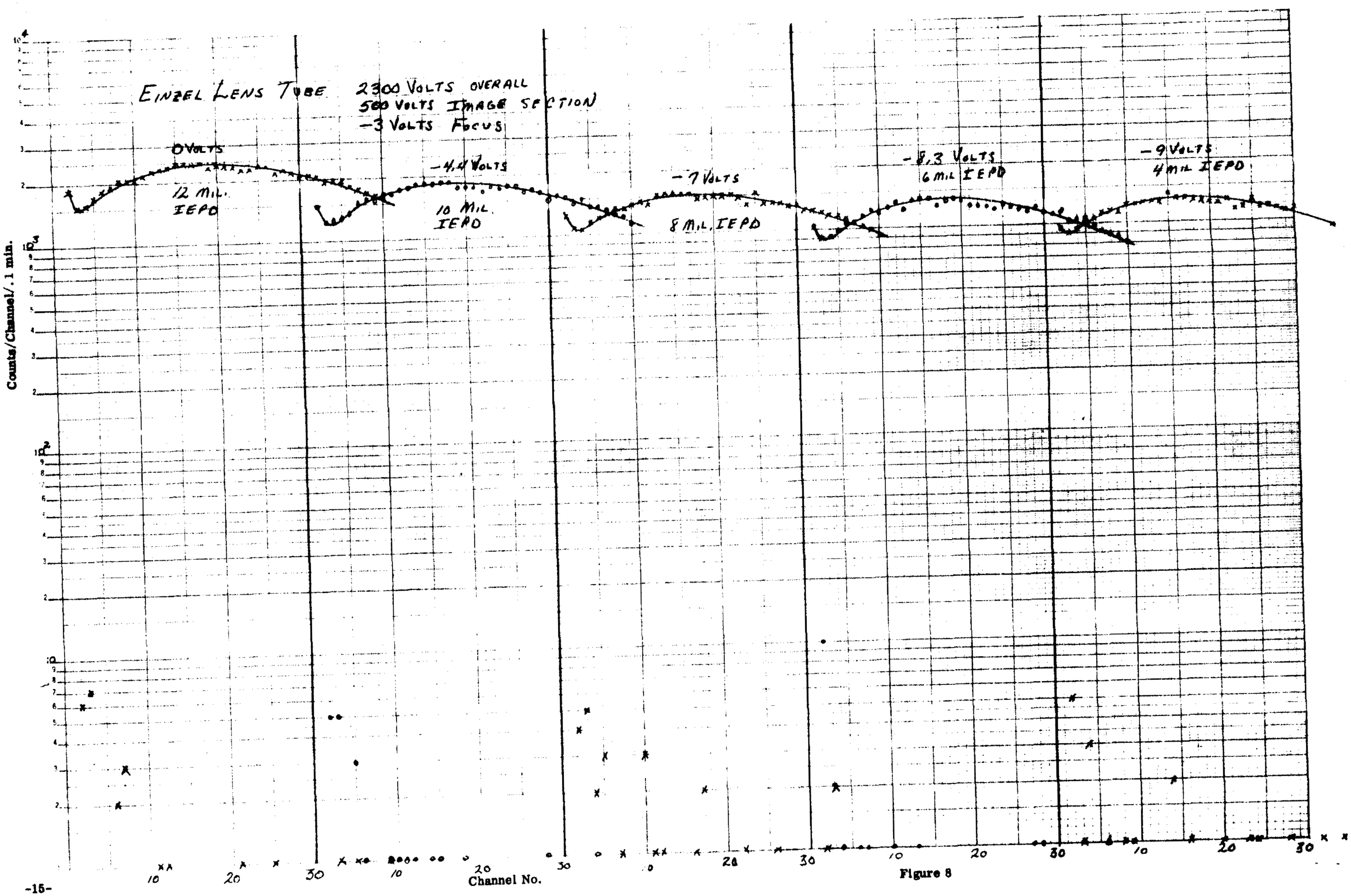

EINZEL LENS TUBE
2300 VOLTS OVERALL
500 VOLTS IMAGE SECTION
-3 VOLTS FOCUS
0 VOLTS
12 MIL. IEPD
-4.4 VOLTS
10 MIL. IEPD
-7 VOLTS
8 MIL. IEPD
-8.3 VOLTS
6 MIL IEPD
-9 VOLTS
4 MIL IEPD
Counts/Channel/.1 min.
Channel No.

Figure 8

APPENDIX I

APPLICATIONS NOTE E4

COOLING CHARACTERISTICS OF

ITTIL MULTIPLIER PHOTOTUBE

APPLICATIONS NOTE E4

COOLING CHARACTERISTICS OF ITTIL MULTIPLIER PHOTOTUBES

The appreciable contribution of thermionic emission from the photocathode to the anode dark current observed in some multiplier phototubes makes possible a reduction in this current and consequently in the dark noise of these tubes by cooling. Figure 1 Curve (a) shows the measured decrease in anode DC dark current, I_{DC}, in an ITTIL FW-118 multiplier phototube (S-1 type) down to photocathode temperatures of about -20 degrees C. The sharply falling dark current, approximately following a Richardson type law, substantiates the predominance of thermionic emission from the photocathode in this tube at these temperatures. A decrease of about an order of magnitude for each 10 degrees C of cooling is observed.

Figure 1 Curve (b) shows the corresponding decrease in the equivalent noise input (ENI)[1] as a function of temperature, compared to the published[2] ENI characteristic Curve (c) for a competitive type tube. The FW-118 starts with a lower ENI characteristic at room temperature (at least partially because of its smaller effective photocathode area) and improves about twice as fast as the competitive detector with temperature.

At anode dark current levels below about 10^{-10} amperes, reliable and significant cooling characteristics can only be observed with difficulty in many multiplier phototubes because of the erratic and nonreproducible contribution of leakage currents (in the tube stem and base and internal parts), external pickup effects, and other low current measurement difficulties. For example, a resistance of 10^{13} ohms across the surface of nominally insulating internal anode pin support (an entirely reasonable value in view of the chemically reactive cathode materials present) can contribute 10^{-10} amperes in the typical operating range of 10^3 volts. This difficulty may be further aggravated when cooling a complete tube envelope if condensation of water vapor across various tube stem and basing lead connections occurs. Noise from this latter source can be particularly troublesome if the condensation occurs between the tube stem and base, where moisture may be trapped in the base cementing process. To avoid this, ITTIL recommends the use of unbased tubes (flying lead construction) or photocathode-only cooling.

1 Defined and measured according to IRE publication No. 62IRE7.S1.
2 RCA tube manual, 7102 tube type.

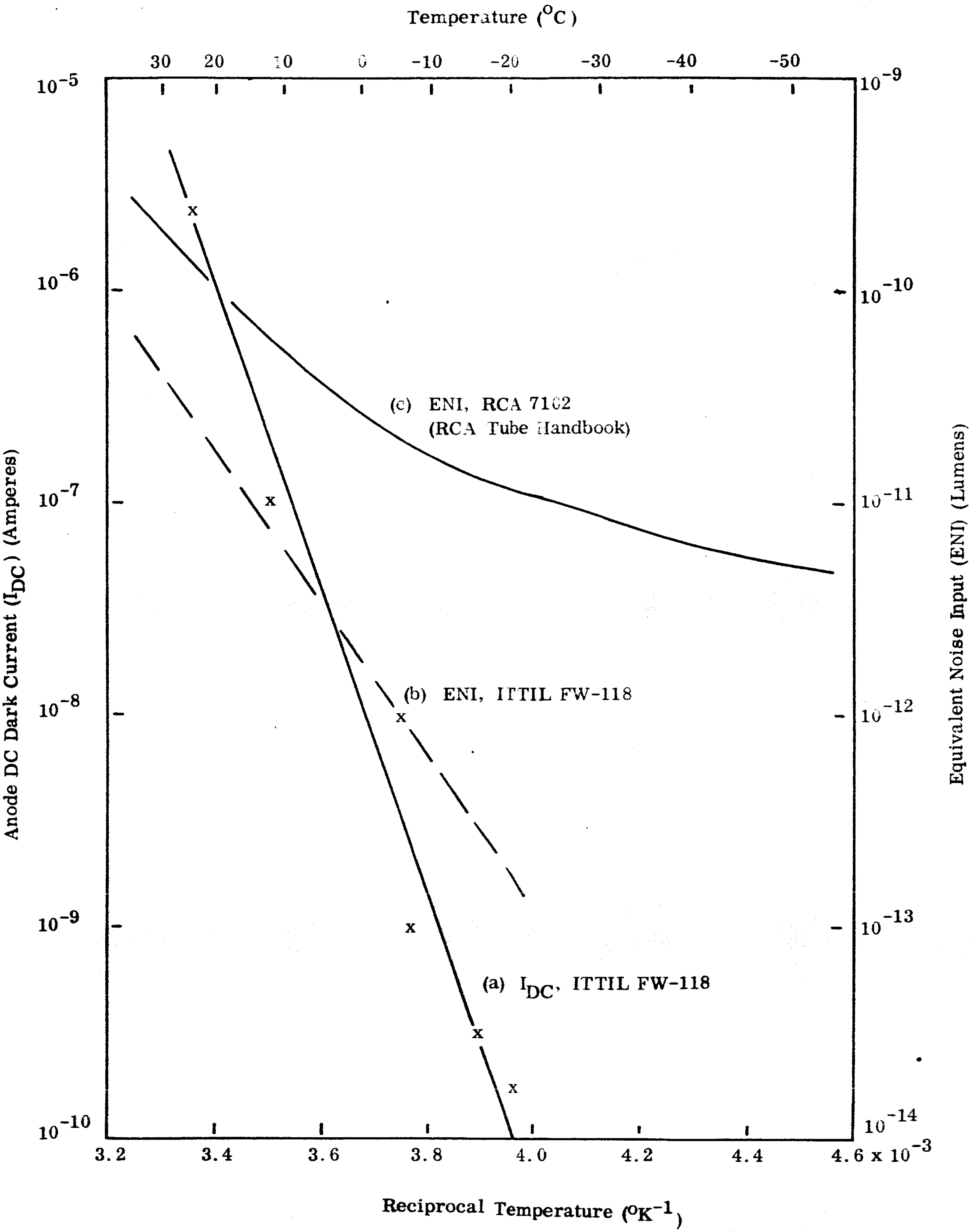


Figure 1 Anode DC Dark Current and ENI Vs Temperature for S-1 Type Multiplier Phototubes

Figure 2 shows a sketch of one type of laboratory cooling test equipment used by ITTIL. The cooled dry gas cools the tube faceplate and thus the photocathode by direct thermal contact, while the warm dry gas keeps the outer window from frosting. For field purposes, thermoelectric photocathode coolers of moderate cooling capability may be entirely adequate.

A recent and unique step taken by ITTIL to minimize internal tube leakage current and therefore improve both the room temperature and cooled dark current-dark noise characteristics, is the addition of an internal guard ring electrode surrounding the anode pin. This guard ring, when operated at quiescent DC anode potential as shown in Figure 3, bypasses surface leakage current around the anode pin and reduces the resultant minimum DC current levels to the order of 10^{-12} amperes or less. If so desired this guard ring can be voltage-driven in the more sophisticated types of feedback electrometer circuits.

For ultra-low light level detection problems, ITTIL normally recommends the use of single electron counting techniques[3,4]. By individually counting the comparatively large pulses produced in the anode circuit of multiplier phototubes resulting from single photoelectrons from the photocathode and biasing off the smaller pulses resulting from leakage current, dynode emission, etc., maximum differentiation between signal and dark noise can be achieved.

Further cooling of ITTIL tubes below the levels shown in Figure 1 is entirely feasible, the tubes being capable of operation at dry ice temperatures and probably as low as liquid N_2 temperatures. A. T. Young of Harvard Observatory has reported[5] a slight increase in over-all sensitivity for these tubes at dry ice and liquid N_2 temperatures combined with a reduction in dark current of at least 5 orders of magnitude at dry ice temperatures, indicating reasonably satisfactory performance, while W. A. Baum has reported[6] dark counting rates below 10 per minute at similar temperatures. ITTIL does not recommend cooling below dry ice temperature unless the temperature cycle is slow enough (a matter of hours) and applied uniformly to the complete tube to prevent strains from developing in the tube envelope, and unless the resultant ultra-low dark thermionic emission rates are known to be desirable (in many

---

3 E. H. Eberhardt, "Multiplier Phototubes for Single Electron Counting", IEEE Tr. of Nucl. Sc., Vol. NS11, No. 2, 48, 1964.
4 ITTIL Research Memos 367 and 387, and Applications Note E5.
5 A. T. Young, Applied Optics, Vol. 2, 51 (1963).
6 W. A. Baum, Vol. II, Astronomical Techniques, U. of Chicago Press, 1962, page 28.

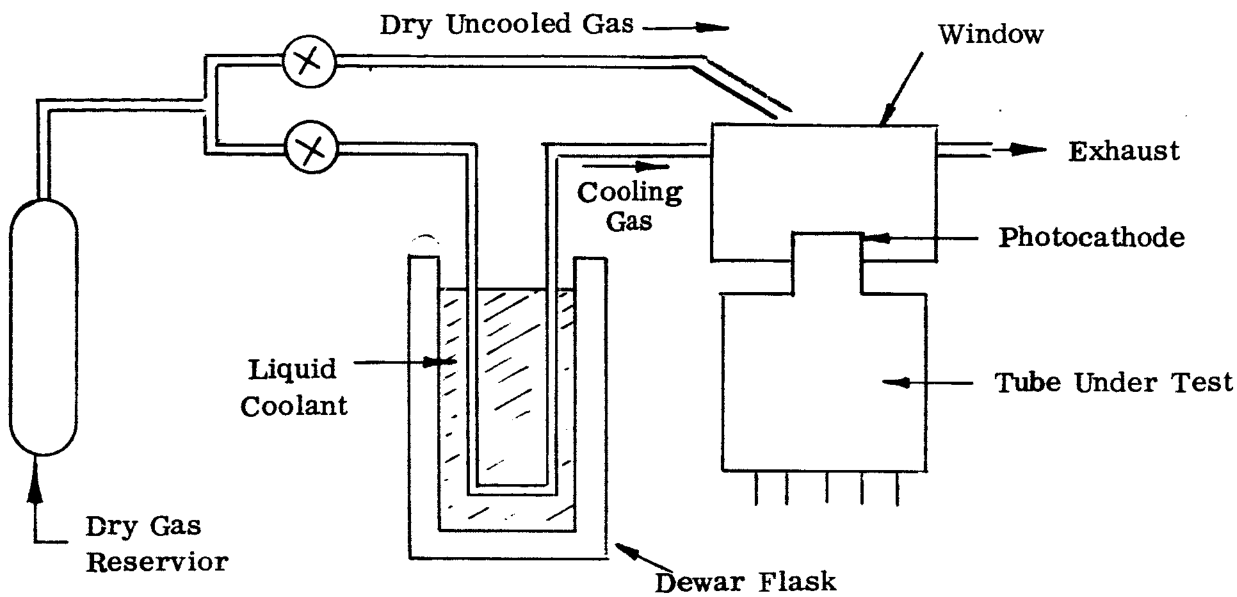


Figure 2 ITTIL Cooling Configuration

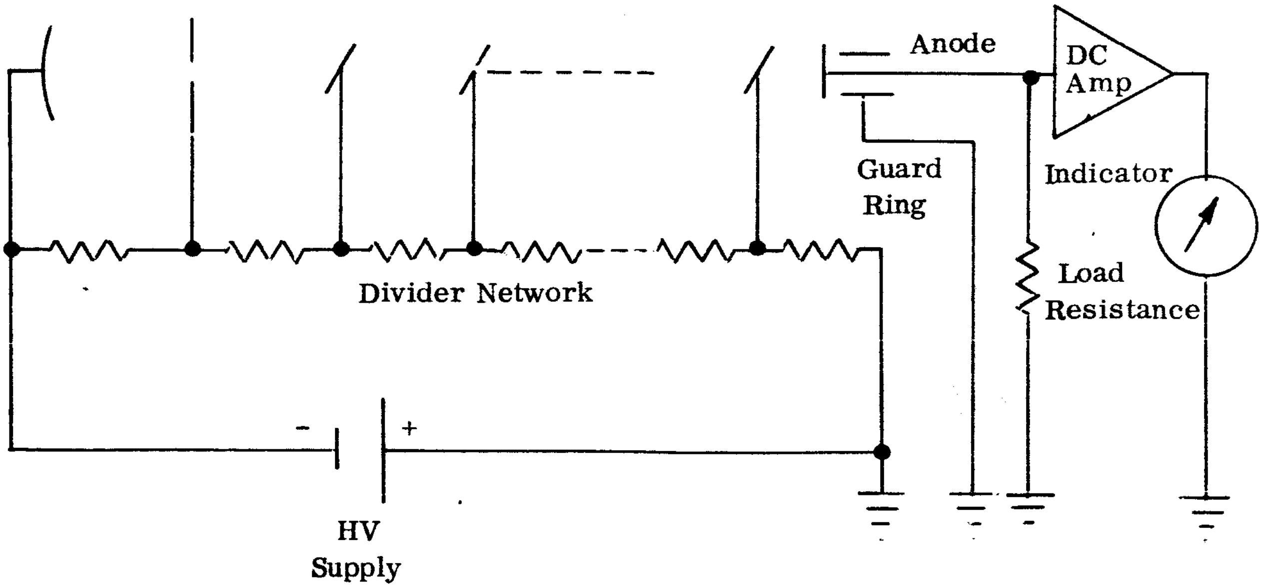


Figure 3 Typical Multiplier Phototube Circuit Using Guard Ring Electrode

applications, background light flux, present on the photocathode in the absence of the signal flux to be detected, radioactive content of the tube parts, and other dark noise sources may normally cause much more noise than photocathode thermionic emission).

The example reported by Baum in which a cooled ITTIL 16 PMI (predecessor of the present FW-118) was operated at a dark counting rate of less than 10 electrons/minute is particularly interesting. Referred to the anode circuit, under the assumption of a gain of 10^6 in the electron multiplier, this is equivalent to less than 3×10^{-14} amperes, a value well below the expected anode leakage current limits. If these 10 dark counts/minute were randomly distributed, as expected, the statistical uncertainty for a one minute observation time would have been $\sqrt{10} \cong 3$ photoelectrons, equivalent to about 13 input photons/second or a total of 750 photons in 1 minute for a peak quantum efficiency of 0.4 percent in the corresponding S-1 photocathode at 8000 Å. The ability to detect flux levels of this magnitude (approximately 3×10^{-18} watts) using single electron counting techniques with a cooled FW-118 multiplier phototube demonstrates the unique capabilities of this detector.

Cooling characteristics of S-11 and S-20 type multiplier phototubes (such as the ITTIL FW-129 and FW-130 types) are not shown in Figures 1 and 2 because of the difficulty in making reliable measurements at the dark emission rates involved. For example, a total thermionic dark count rate of only 30 electrons/second at room temperature was observed[3] in one sample ITTIL FW-129 tube. This magnitude is believed to be typical of present S-11 and S-20 tubes. Based on tentative experimental measurements it is believed that these thermionic emission dark current count rates will also fall rapidly with cooling.